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Technical Report

DESALINATION PROCESSES FOR MILITARY APPLICATION

June 1968

NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California 93041

DESALINATION PROCESSES FOR MILITARY APPLICATION

Technical Report R-587

Y-F015-20-02-029

by

J. S. Williams and Allan S. Hodgson, Ph D

ABSTRACT

This report summarizes the desalination processes currently available which lend themselves to military application. Membrane processes (electrodialysis and reverse osmosis) and thermal processes (multistage flash distillation and vapor compression distillation) are explained, and examples of the use of each type of equipment are cited. Design criteria are given for multistage flash distillation units utilizing waste heat from diesel generators. An optimization procedure is also given for similar units using direct-fired boilers.

EVALUATION SHEET

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Author J. S. Williams and Allan S. Hodgson, Ph D

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INTRODUCTION

One of the most important utilities at any military base is the water supply system. There are probably no two bases which have identical systems because of such variables as water availability, raw water quality, and per capita demand. Therefore, the difference in systems may vary from slight to very great. One factor which can cause a big difference is raw water quality. This report will attempt to describe the alternative processes available for obtaining potable water from either brackish water or seawater. The processes described will be limited to those which are commercially available and which lend themselves to military application.

Because the demands placed upon military equipment are often significantly different from those placed upon industrial and municipal equipment, military specifications are used for procurement. Features such as mobility, rugged construction, operational simplicity, and logistic economy are all stressed. An exception would be an installation similar to the one at the Naval Station, Guantanamo Bay, Cuba. This is a large, permanent plant, operated by civilian personnel, supplying over two million gallons of water per day to what is, in effect, a small city. And as long as U. S. military forces are deployed around the world, there is a strong likelihood that more plants of this type will be built.

It can be seen, therefore, that there are really two different requirements for water desalination systems, depending upon whether the systems are field units or permanent units. For purposes of definition, any base with a life expectancy of over 5 years will be termed permanent. Possibly a better definition would be any base which was designed by the Engineering Division, Naval Facilities Engineering Command (NFEC), for on-site construction by the Construction Division, NFEC. This would leave the equipment provided by the Military Readiness Division of NFEC as field units and these are usually assemblies in the Advanced Base Functional Components.

SALINE WATER SOURCES

Navy bases are generally located near the ocean, from which an unlimited supply of salt water can be drawn with relatively little expense. Some bases are located on estuaries or rivers which are brackish due to tidal action. However, NFEC is often called upon (as in Southeast Asia) to assume the responsibility of construction for Army and Air Force bases which are located inland. Even here, there is always the possibility that the water source will be saline and that desalination will be required to make it potable.

The cost of manufacturing water by desalination is usually higher than the cost of developing fresh water from underground or surface sources. In general, therefore, every effort should be made to utilize local fresh water sources even though these may require extensive treatment in the form of clarification and purification. In the event that saline water is available and the only fresh water is a marginal amount of ground water, a decision must be made as to which source to utilize. When a base is expected to have a short life (under 10 years), it may be more sound economically to desalt ocean water than to drill a large number of wells, the cost of which is not recoverable. The desalination equipment can be reused at different locations thus saving substantial capital expenditure.

DESALINATION PROCESSES

At this time, there are only two basic methods of desalination which can be considered commercially available: membrane processes and thermal processes. The membrane processes include electrodialysis and reverse osmosis. The latter is quite new, and very little operating experience is available. There are a number of thermal processes which either have been or are being used for desalination.

The most popular thermal process today is multistage flash distillation. Today 1-million-gallon-per-day (gpd) multistage flash distillation plants are quite common, and a 150-million-gpd plant is planned for completion within a few years on a man-made island off the coast of Southern California. Since World War II the vapor compression distillation unit has been the mainstay of military desalting equipment ashore. Generally limited to capacities under 25,000 gpd, these units can be made to be portable and self-sufficient, with a high thermal efficiency.

The double- and triple-effect evaporators are now seldom being built for this service. The same is true of the submerged tube evaporator, although there are still quite a few installations using all of the above evaporators.

Membrane Processes

A membrane may be considered a selective filter through which, under certain conditions, some substances will pass relatively freely while others are retained. A force is required to separate substances through the membrane. In electrodialysis, the necessary driving force is provided electrically and the impurities pass through the membrane, leaving fresh water. Reverse osmosis employs a pressure as the driving force, but the impurities are retained by the membrane and the fresh water passes through.

Electrodialysis. From the standpoint of research and development accomplished to date, electrodialysis is the most advanced of the membrane processes. An electrodialysis conversion assembly is essentially an electrolytic cell which contains two different types of ion-selective membrane. One of the membrane types allows the passage of positive ions, or cations, and the other allows the passage of negative ions. The electrolytic cell provides the driving force for the ions. A basic electrodialysis cell is shown in Figure 1. The cation-permeable membrane allows passage of the positive sodium ions, and the anion-permeable membrane allows passage of the negative chloride ions, yielding fresh water between the membranes.

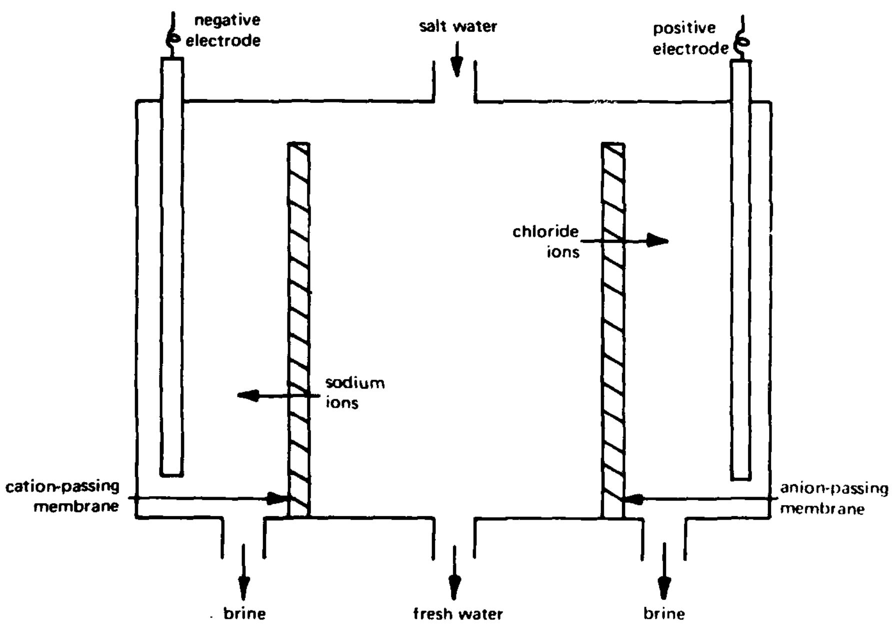


Figure 1. Electrodialysis cell.

The amount of electric current required in the unit depends on the amount of salt to be removed. Therefore, the cost of the energy consumed in the process depends on the concentration of salt in the feed water. The relationship between electric current requirements and salt content is the main reason that electrodialysis is favored for brackish water instead of seawater. However, if the cost of membranes and processing equipment can be reduced sufficiently, electrodialysis may become economically feasible for seawater conversion, particularly in areas where electric energy is available at low costs. Research sponsored by the Office of Saline Water is currently being conducted to investigate the feasibility of operating the electrodialysis process at elevated temperatures. High temperatures result in low electrical resistance of the electrolyte and, therefore, in lower electric power requirements. High-temperature operation shows promise of reducing power requirements sufficiently to make electrodialysis attractive for seawater conversion.

The application of electrodialysis to brackish water presents a problem not usually associated with seawater conversion. The chemical composition of seawater is relatively constant, whereas that of brackish water varies greatly. Consequently, the design and operation of equipment is influenced by the amount and type of constituents present in the water, for these constituents will determine the pretreatment needed, the amount of scale that will form, and the number of stages required in the process.

The membranes used in an electrodialysis unit are produced by chemically treating a base material such as polystyrene. A number of fabrication techniques are being investigated. Some of the techniques give membranes of relatively short life but low initial cost, while others give membranes of longer life and higher cost. The development program is directed toward obtaining membranes which give the best compromise between life, ion selectivity, and hydraulic and electrical characteristics.

The Naval Civil Engineering Laboratory (NCEL) first became involved in electrodialysis in 1955 when a brackish water unit was evaluated.[1] It was recommended at the time that a few units be purchased and installed to obtain operational data from the field. One very small unit was sent to the Philippines for use at a communications station near Subic Bay. A brackish water demineralizer is illustrated in Figure 2.

Following the testing of the brackish water unit, a seawater unit was evaluated.[2] Satisfactory desalination was obtained; but although equipment costs were the same for both electrodialysis and vapor compression distillation, operation and maintenance costs for electrodialysis were three to four times those for vapor compression distillation.

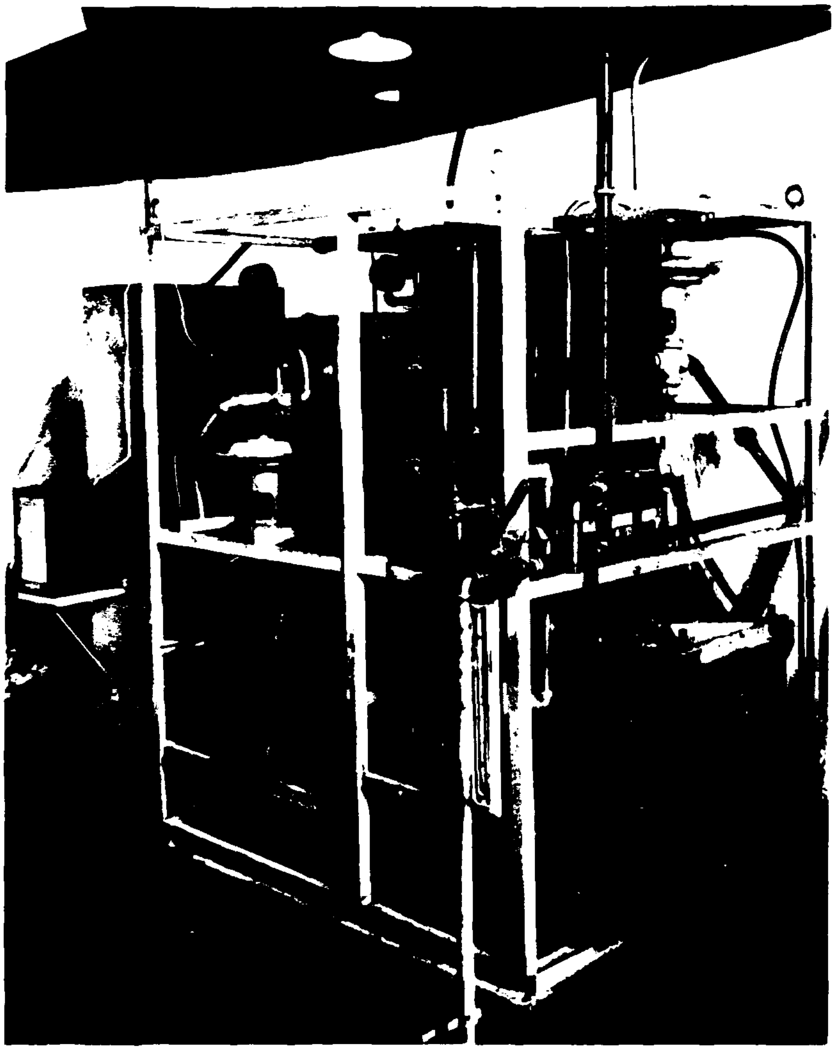


Figure 2. Brackish water demineralizer.

Reverse Osmosis. When pure water and a salt solution are on opposite sides of a semipermeable membrane, the pure water diffuses through the membrane and dilutes the salt solution. This phenomenon is known as the process of osmosis. The pure water flows through the membrane as though a pressure were being applied to it. The effective driving force causing the flow is called osmotic pressure. The magnitude of the osmotic pressure depends on the characteristics of the membrane, the temperature of the water, and the concentration of the salt solution. By exerting pressure on the salt solution, the osmosis process can be reversed. When the pressure on the salt solution is greater than the osmotic pressure, fresh water diffuses through the membrane in the opposite direction to normal osmotic flow.

The principle of reverse osmosis is illustrated in Figure 3. It can readily be seen how this principle can be applied in the conversion of saline water.

A diagram of the reverse osmosis process is shown in Figure 4. The salt water is pumped through a filter and raised to operating pressure by a high-pressure pump and then introduced into the desalination unit. A portion of the water permeates the membranes and is collected as product water at the bottom of the unit. The brine is discharged at the top of the unit. When desired, some of the brine may be mixed with incoming saline water and recirculated. Figure 5 shows a reverse osmosis unit installed on a barge.

Some of the important advantages of the reverse osmosis process are:

1. Low energy consumption. Since no change of phase is involved, the only energy consumed is the electrical energy needed to drive the pumps.

2. The processing equipment is relatively simple, resulting in low equipment costs.

3. The operation of the process at normal temperatures minimizes problems of scale and corrosion.

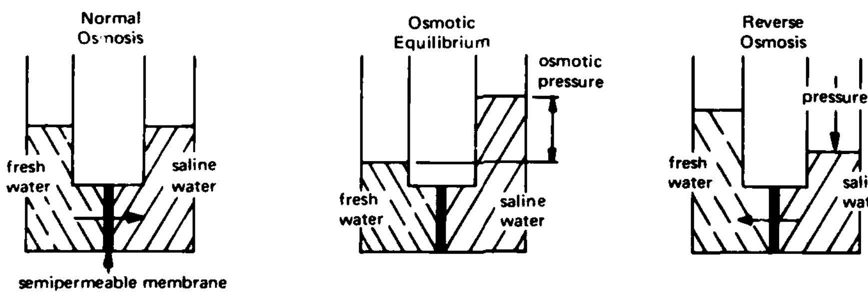


Figure 3. Principle of reverse osmosis.

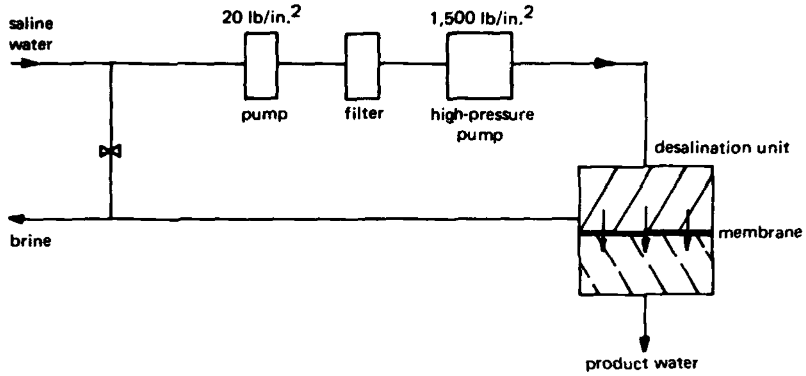


Figure 4. Diagram of reverse osmosis process.

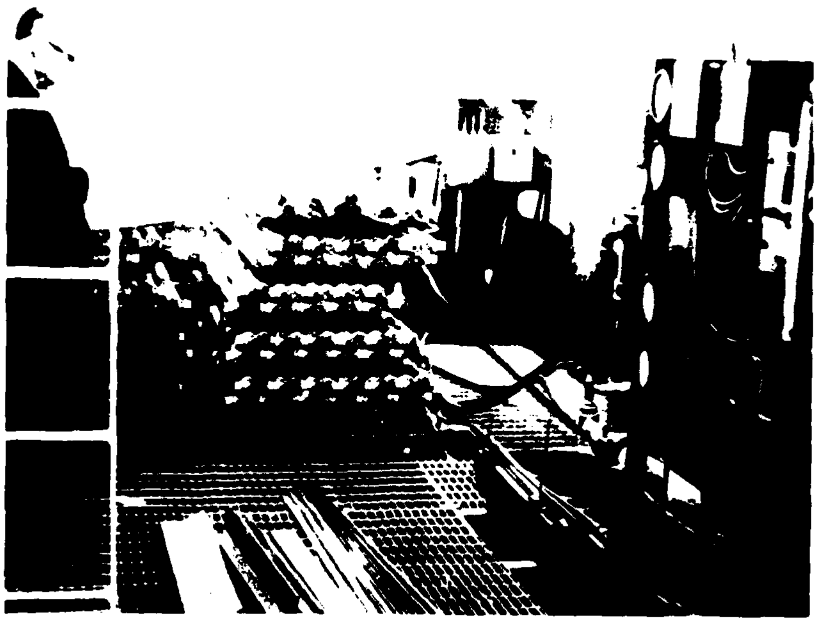


Figure 5. 5,000-gpd reverse osmosis unit installed on a barge.

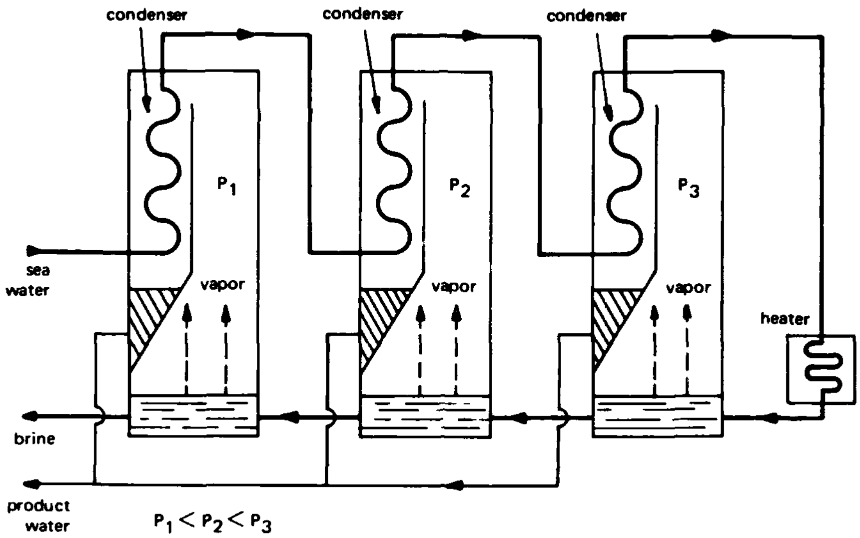


Figure 6. Multistage flash distillation process.

At the present time a major limitation of this process is the feed water concentration which can be handled efficiently. This membrane process is considered promising for brackish water, and research is being conducted to increase its effectiveness for seawater.

Thermal Processes

The two thermal processes currently employed by the military for desalination are multistage flash and vapor compression distillation. In both processes an input of energy is required to convert a part of the saline water to steam, which is condensed to give the fresh product water. The difference between the two processes is that for multistage flash distillation the input is heat energy and for vapor compression the input is mainly mechanical energy.

Although the processes are in principle simple, there are a number of factors which must be taken into account when designing evaporation equipment. Heat transfer must be accomplished as efficiently as possible, taking into account such factors as boiling point elevation, effect of hydrostatic head, heat transfer coefficients, scaling, entrainment, and removal of noncondensable gases.

Multistage Flash Distillation. The multistage flash distillation process (Figure 6) makes use of the fact that water boils at progressively lower temperatures as it is subjected to progressively lower pressures. The seawater is heated and then introduced into a chamber where the pressure is sufficiently low to cause some of the water to boil instantly or "flash" into steam.

Vaporization of some of the water results in a lowering of temperature of the remaining brine. The brine then flows into the next chamber, more of the water flashes into steam, and the temperature is again reduced. Condensation occurs when the steam comes into contact with the heat exchanger through which the incoming salt water flows before passing through the brine heater. In this way the heat which must be removed from the steam in order to condense it into fresh water is transferred to the seawater, supplying it with some of the heat energy required to cause it to boil.

The arrangement shown in Figure 6 is very efficient for the recovery of heat energy. Ninety percent of the heat energy added to the salt water before it enters the first chamber is transferred to new salt water before it enters the heater. The brine which is returned to the sea after passing through the last stage is somewhat hotter than the incoming seawater. This temperature difference accounts for most of the heat loss of the plant. Although it is possible to recover even more than 90% of the heat energy, it is more economical to reject the final 10%.

Multistage flash distillation is quite promising for use by the military The necessary thermal energy can be furnished by a direct-fired boiler or by utilizing waste heat from a diesel-electric power plant. The latter provides a very economical system since the salt water heater in the multistage flash distillation system acts as the cooling system for the diesel. Additional heat is available from the diesel exhaust. Almost all diesel manufacturers can supply equipment which has been designed for waste heat recovery. Figure 7 shows a typical example of what can be accomplished.

Almost all Navy bases have an electrical demand which will supply enough waste heat for the base water plant at a minimum demand of 30 gallons per man per day. A waste heat system has several advantages. If the electrical power load tends to fluctuate widely at periods of low electrical demand, a resistance load can be used to heat more water and increase the water plant production. Both electrical and water supply systems are thus stabilized. This capability of a waste heat system reduces maintenance on diesels, which tend to foul at low loads, and allows a smaller and less costly, although less efficient, water plant installation. This type of system would generally be used where the average daily electrical load was not sufficient to provide enough heat unless a very large number of stages were used in the evaporator.

When the electrical load fluctuates, but the average is high enough to provide adequate waste heat for the flash evaporator to meet the water demand, a design developed at NCEL may have possibilities. A special automatic control system enables the evaporator to operate effectively over a very wide range of heat input. Basically, the feed flow rate varies while the pressure and temperature conditions remain fairly constant. Details of this system will soon be published in an NCEL report.

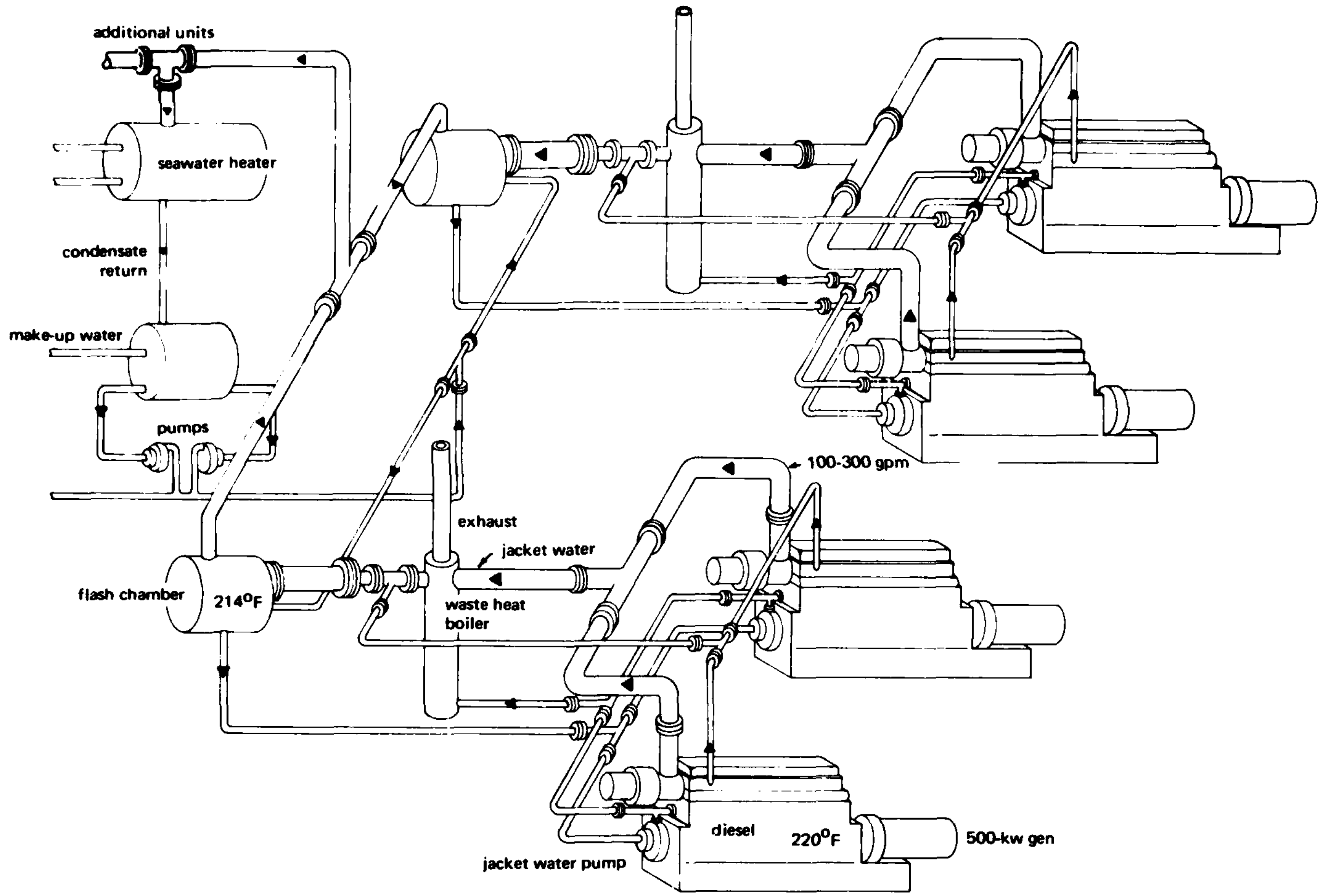


Figure 7. Diesel generator waste heat recovery system.

Examples of multistage flash distillation units at military bases are not numerous, but they cover almost the entire capacity range. Three 750,000-gpd units, one of which was moved from San Diego, form the 2-1/4-million-gpd plant at Guantanamo Bay (Figure 8). Heat is furnished by steam bled from the turbines generating the electrical power for the base. It is a dual-purpose plant, each unit sharing the seawater and steam. Thirty thousand gallons of seawater are split five ways, with each evaporator taking 6,000 gallons and each of the two boilers using 6,000 gallons in its condensor.

The Southeast Division of NFEC is responsible for the design and installation of two 60,000-gpd waste heat multistage flash distillation units at the Air Force base on Ascension Island in the south Atlantic. These units derive their heat from the cooling system of the diesel-electric power plant.

For several years a smaller 15,000-gpd sixteen-stage multistage flash distillation unit has been operating at McMurdo Sound in the Antarctic. A second unit will probably be installed soon.

Another small plant rated at 10,000 gpd has been in operation at the AUTEC facility in the Bahamas for a number of years.

Figure 8. Desalination plant at Guantanamo Bay.

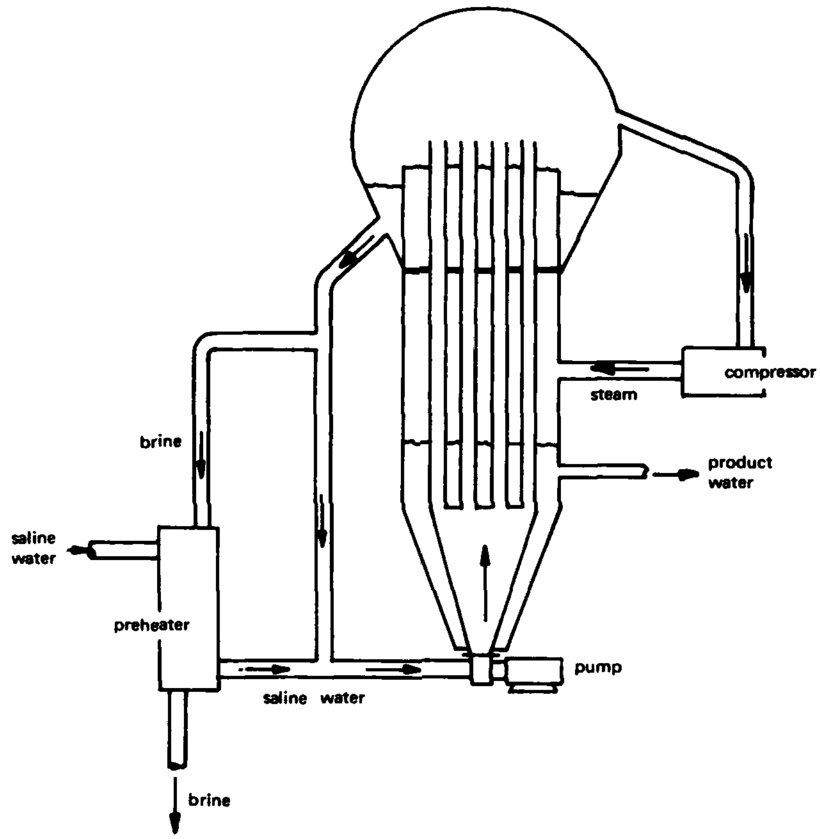


Figure 9. Vapor compression process.

Vapor Compression Distillation. The vapor compression process is based on the principle that when water vapor is compressed its temperature rises. Thus, it is possible to raise the temperature of the vapor produced by boiling seawater at atmospheric pressure by 10°F if it is compressed to 18 lb/in.^{2} This temperature difference is necessary to provide the driving force to transfer the latent heat of the vapor to the seawater; the seawater boils to produce fresh vapor for compression, and the vapor condenses as product water.

The principle of vapor compression distillation is illustrated in Figure 9. Saline water passing through the tubes is heated by the condensing steam surrounding the tubes. Heated brine is then flashed into the low-pressure chamber; this produces vapor which is fed to the compressor, where it is compressed and returned to the tube area, providing heat to flash more water. The condensate falls to the bottom to become product water. An 85-gph unit is illustrated in Figure 10.

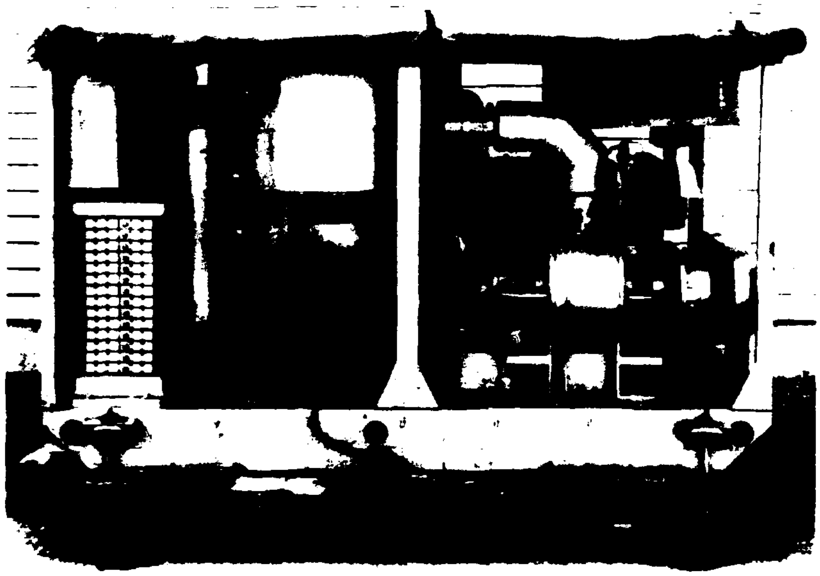


Figure 10. 85-gph vapor compression evaporator.

Ideally, once the latent heat has been supplied to the system, the process would continue, requiring only the mechanical energy to compress the vapor. In practice, this is not possible, but to approach this condition within economic feasibility is a worthwhile objective.

A flow diagram of the latest type of vapor compression distillation unit is shown in Figure 11. By tracing the three liquid streams and by observing the engine waste heat reclamation system, it can be seen that maximum utilization is made of energy input, in this case diesel fuel. The latest design changes in the vapor compression still are the horizontal tube, film evaporator, and a centrifugal compressor; such a unit has been evaluated at NCEL.[3] For years the evaporator had the standard configuration of vertical tubes with a central downcomer or, in some cases, external downcomers. Some manufacturers added an impeller which forces circulation in the tubes. When the seawater is applied in the form of a coarse spray over a horizontal bundle of tubes, the heat transfer coefficient is improved so that a 30% reduction in tube surface is possible. The centrifugal compressor reduces weight and vibration and is much quieter than the positive displacement compressor. A unit of this design constructed entirely of aluminum is still to be evaluated.

Although by no means a new concept, the development of the vapor compression process came about during World War II when the campaign in the Pacific posed the need for potable water at localities where only salt water was available. These early units were quite inefficient, producing less than 100 pounds of water per pound of diesel fuel or gasoline, and they required constant attention by the operator. Work at NCEL prior to the Korean conflict lead to many improvements, but the basic design was much the same. Water-to-fuel ratios had increased to about 200 to 1, but scale that formed in the units reduced this figure rapidly during operation. An acid-cleaning procedure was developed at NCEL which permitted continuous operation at optimum performance.[4] A small amount of acid was injected into the evaporator at 8-hour intervals with no necessity for shut-down. At the same time the improved performance permitted use of smaller engines, thus increasing the water-to-fuel ratio to over 300 to 1. Controls which were self-actuated by floats or vapor pressure made operation almost automatic.

MEMBRANE DEVELOPMENT

The successful application of the reverse osmosis process is for the most part dependent on the success of the membrane development program. In general, the development of membranes is aimed at obtaining long membrane life and high rates of fresh water diffusion per square foot of membrane surface area at a reasonable cost.

The apparent simplicity of the reverse osmosis process makes it quite attractive for military use. As a result, NCEL has watched the membrane development with interest. A contract was awarded to Universal Water Corporation to conduct research and development on improved membranes for seawater service and to build a prototype model upon completion of the membrane study. The membrane study will be continued under the direction of the Office of Saline Water, and NCEL will conduct development studies of equipment.

Several suppliers are marketing reverse osmosis units. Most of these have been designed for brackish water service, although all the suppliers seem to be interested in the seawater application. Havens Industries in San Diego has built two 5,000-gpd two-stage units for the Navy. These are installed on barge complexes going to Vietnam. Havens, as well as the Universal Water Corporation, uses tubular membranes in its equipment.

Other suppliers who have contributed a great deal to membrane technology are Aerojet General and the General Atomic Division of General Dynamics Corporation. General Atomics makes a spiral-wound module and Aerojet makes a module with flat membranes and spacers arranged in a stack enclosed in a pressure vessel.

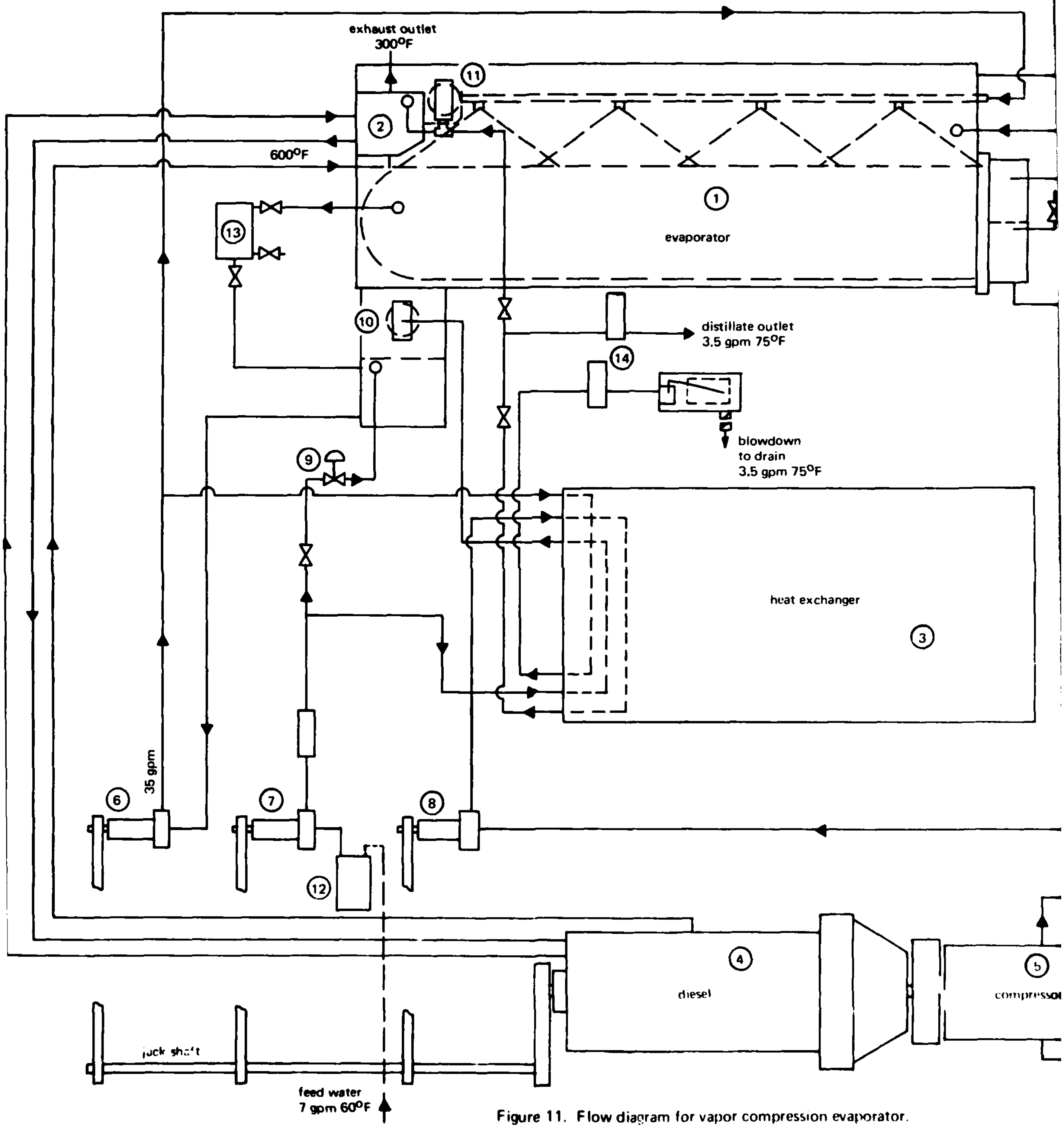
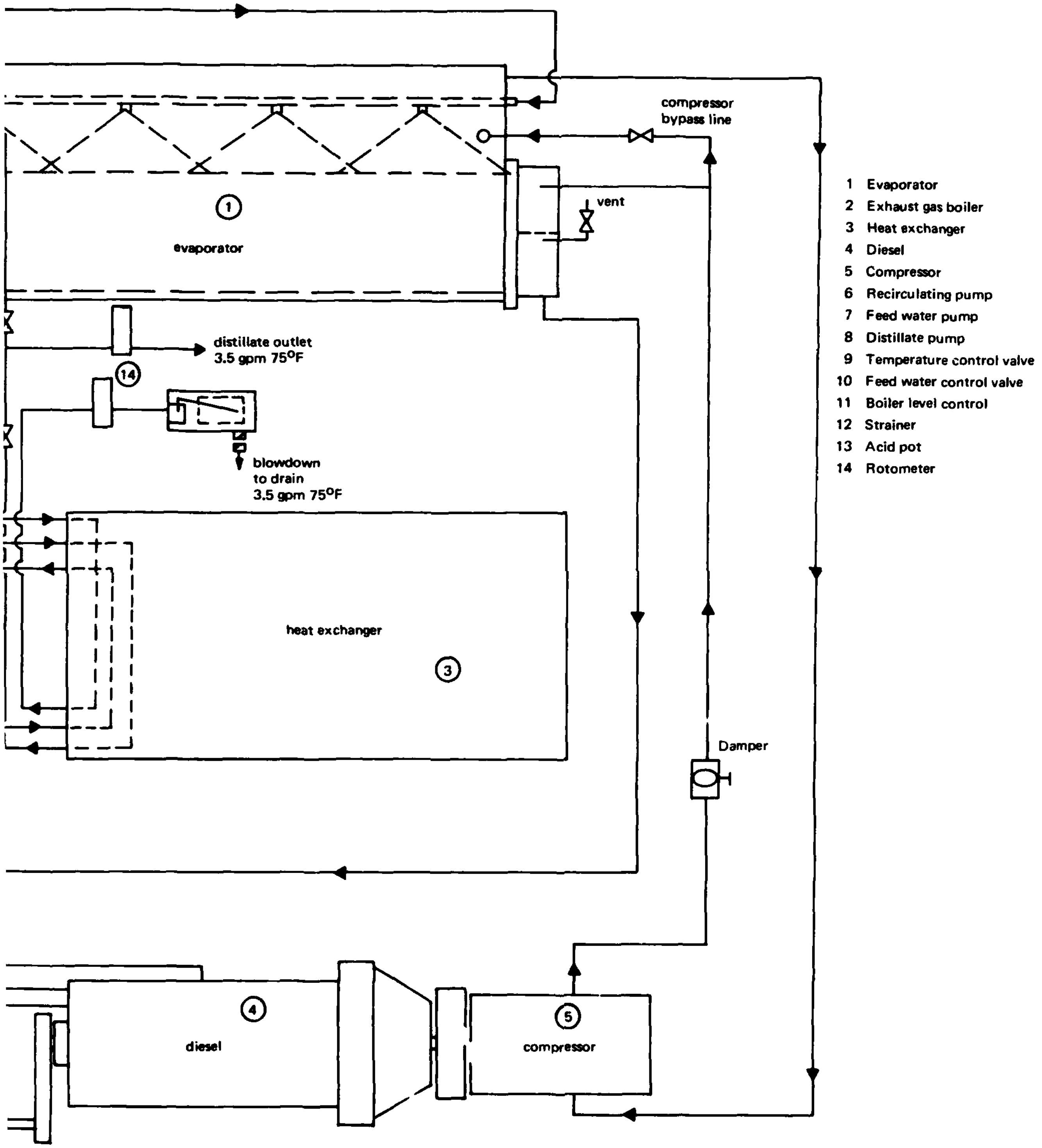


Figure 11. Flow diagram for vapor compression evaporator.

A



igure 11. Flow diagram for vapor compression evaporator.

B

The chief advantage claimed for tubular membranes over a spiral or a stack arrangement is the ease of keeping the membrane module clean without using high-performance filters. Field experience will be necessary to prove this point, however. Another point in question regarding reverse osmosis membranes is the problem of long-term storage. Membranes now in production must be kept moist and not allowed to be overheated. Here again only experience will provide reliable data. Membranes may also be sensitive to a pH above 7.5. For many waters, including seawater, the pH must be adjusted by the addition of acid. This requires some type of feeding device. The manufacturer may also recommend the addition of chemicals, such as sodium sulfite and sodium phosphate, to prevent scale deposition on the membrane surface. This requires another feeder. Chlorination of the product water is necessary, so one more feeder is added.

CRITERIA FOR SELECTING DESALINATION METHODS

When a decision has been made to use desalination for the potable water supply, the design engineer may very well ask, "What system do I use?" The selection should be based on sound engineering and economics. To apply these, he must have good knowledge of the state of the art as it pertains to military usage. He will not have time to make a lengthy literature search, visit other installations, or evaluate all the claims made by equipment suppliers who will descend upon him. It appears that his best approach is to resort to a condensed version of the state of the art presented in tabular and graphic form. Such presentations have been done quite effectively with other subjects in the NFEC design manuals. The following criteria should be reviewed when a method of desalination is being selected:

1. ***Application.*** At installations near the seashore where fresh water is not available or cannot be transported economically, some method of salt water conversion should be provided.

2. ***Methods available.*** In NFEC Design Manual 5, Tables 9-27 and 9-28 describe the more common methods of salt water conversion.

3. ***Factors influencing selection of method.*** The choice of method depends upon a number of factors.

   a. A temporary installation (less than 5 years) should utilize portable equipment. The number of units should be kept to a minimum by using the largest practical size available.

   b. A permanent installation at an existing facility should be chosen on the basis of the long-range cost of the system which will best satisfy the needs. A comparison should be made between direct energy sources and waste heat sources, construction and operating costs at different building sites, and the cost of a single- and a dual-distribution system.

c. A permanent installation for new construction should be planned during the initial base development planning and if necessary should influence the selection and location of other base components.

d. The quantity and quality of potable water required should be stated clearly in terms of how many gallons of water of a certain quality will be required and on what time schedule if base growth is expected.

e. Energy sources available should be listed and evaluated as to their suitability for use in the desalination system.

f. Location of plant with respect to salt water source may influence the location of other components.

g. Concentration of salt water will dictate to some extent the type of system which can be installed. Water having less than 5,000-ppm total dissolved solids can be processed in membrane systems. Water of higher concentration may be processed by thermal systems or some membrane systems.

4. ***Related criteria***. Certain criteria related to salt water conversion systems appear in the NFEC design manual series. Specifically, the sections related to water supply systems, heating systems, diesel-electric generating systems, steam heating plants, and high-temperature-water heating plants should be examined.

An example appears in Appendix A which relates these criteria to the design of multistage flash distillation units that utilize the waste heat from diesel generators. If no waste heat is available, the energy to operate the unit will be supplied by a boiler. An example of cost optimization for multistage flash distillation units that utilize direct-fired boilers is given in Appendix B.

CONCLUSIONS

1. The membrane processes have, at present, a limited application and are more suitable for brackish water than seawater. A rapid advancement in membrane technology may lead to improved reverse osmosis and electrodialysis desalination equipment.

2. The thermal processes are well established and efficiencies have increased in recent years. Technological advancement in these processes will probably not be spectacular, but consist of a series of successive, small improvements.

3. Waste heat from diesel generators is a convenient and effective means of operating a multistage flash desalination unit.

RECOMMENDATIONS

1. Reverse osmosis equipment will become increasingly more suitable for Navy requirements as the design of the membranes and complete units improves; therefore, the following five-point program is suggested.

a. Survey the field in depth and evaluate the potentials and limitations of available materials and mechanisms.

b. Prepare system concepts for different Navy requirements such as advanced bases, aircraft carriers, and barges.

c. Using systems analysis, define the cost effective system for each requirement.

d. Perform experimental work required to develop the concepts.

e. Build and test experimental units.

2. Desalination by freezing techniques is becoming economical for small units. A study of this process should be made to determine its suitability for advanced bases.

3. Research and development should be directed toward the accumulation of quantitative information to improve distillation units. Such factors as the effect of geometric configuration on heat transfer, scaling mechanisms, effects of suspended solids on boiling heat transfer, and high-temperature operation should be included.

Appendix A

DESIGN CRITERIA FOR MULTISTAGE FLASH DISTILLATION UNITS THAT UTILIZE WASTE HEAT FROM DIESEL GENERATORS

It is possible to formulate design criteria for a multistage flash desalination plant given only two parameters: the amount of water required and the amount of heat available. It will be assumed that the water demand has been established. It can also be assumed that the electrical load has been established and includes an estimated hourly breakdown. Waste heat is available from the engine jacket coolant or the exhaust gas or both. The jacket cooling system may be either a water recirculating type or a boiling-condensing type. The amount of heat rejected is approximately the same in either case, but the temperature level of the boiling-condensing system is higher. Figure A-1 gives average values for waste heat available from diesel engines. More accurate figures may be obtained from the engine manufacturer. From Figure A-2 the thermal economy for the desalting plant can be obtained. This is expressed in pounds of product water per 1,000 Btu input. Figure A-3 provides the condenser heat transfer area in terms of sq ft/1,000 gpd distillate production. The area between the dotted lines is generally considered to be the normal design range. The curves are relatively flat in this portion, permitting some leeway in the selection of the number of stages. For the first approximation, the midpoint is suggested. The heat transfer area per 1,000 gpd is read off the left-hand side of the chart, and the total area is found by multiplying this figure by the number of 1,000-gpd capacity required. Then, from Figure A-4, an estimated cost of equipment is obtained. The following examples are given to illustrate the use of the figures:

Example 1a

Water demand—60,000 gpd
Average electrical load—2,000 kw (three 1,000-kw units at 2/3 load)
(only engine jacket and oil cooler heat used)

Step 1. Enter Figure A-1 at the bottom at 1,000 kw. Move vertically up to "oil cooler" line and project horizontally to the 2/3 load line to read 0.3 million Btu/hr. Also move up to "water jacket" line and project horizontally to 2/3 load line to read 1.2 million Btu/hr. The heat available from each unit is equal to the sum, or 1.5 million Btu/hr each. Thus total heat available is 1.5 multiplied by three, giving 4.5 million Btu/hr.

Step 2. To determine the thermal economy, use Figure A-2 and draw a horizontal line from the 4.5 million Btu/hr value and a vertical line from the 60,000-gpd value. These intersect at a thermal economy of 4.8 lb/1,000 Btu.

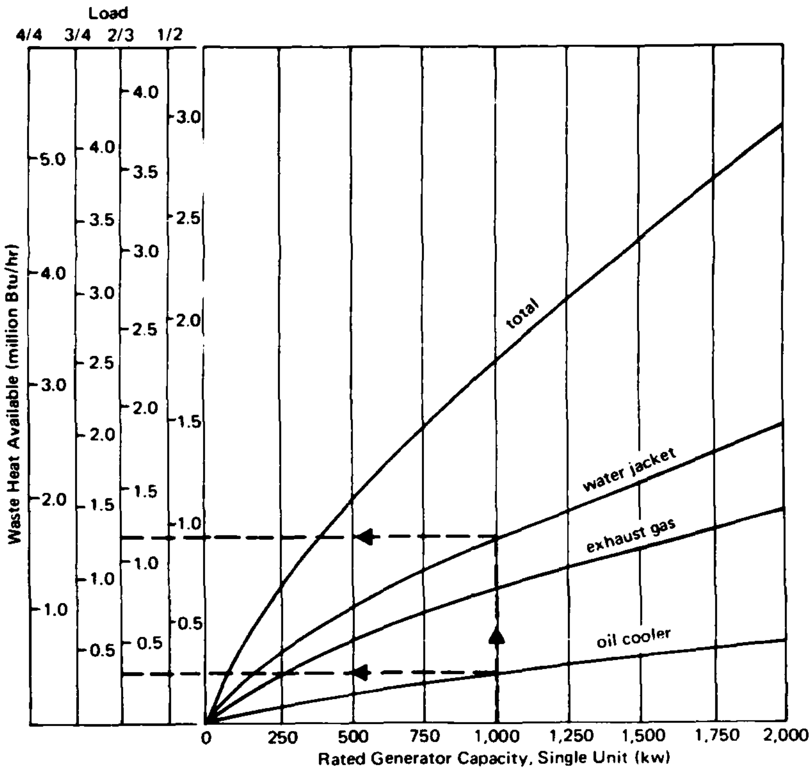


Figure A-1. Waste heat available from diesel generators.

Step 3. On Figure A-3 a line corresponding to a thermal economy of 4.8 lb/1,000 Btu is quite flat beyond the 20-stage point, and 20 stages will be selected. Projecting to the left gives 70 sq ft/1,000 gpd or a total of 4,200 sq ft for the 60,000 gpd required from the unit.

Step 4. From Figure A-4 the cost of equipment is found by projecting vertically from the heat transfer area of 4,200 sq ft to the line and horizontally to the cost of the unit. Thus the cost is $110,000 for a single 20-stage multistage flash distillation unit.

Example 1b

It may be shown that it is more economical to use one single unit for multistage flash distillation than several small units to give an equivalent output of fresh water. The cost of two 30,000-gpd units may be calculated by following the same procedure outlined above and by using the same quantity of waste heat. The total cost resulting from the calculation is $132,000, which is greater than that for the single 60,000-gpd unit.

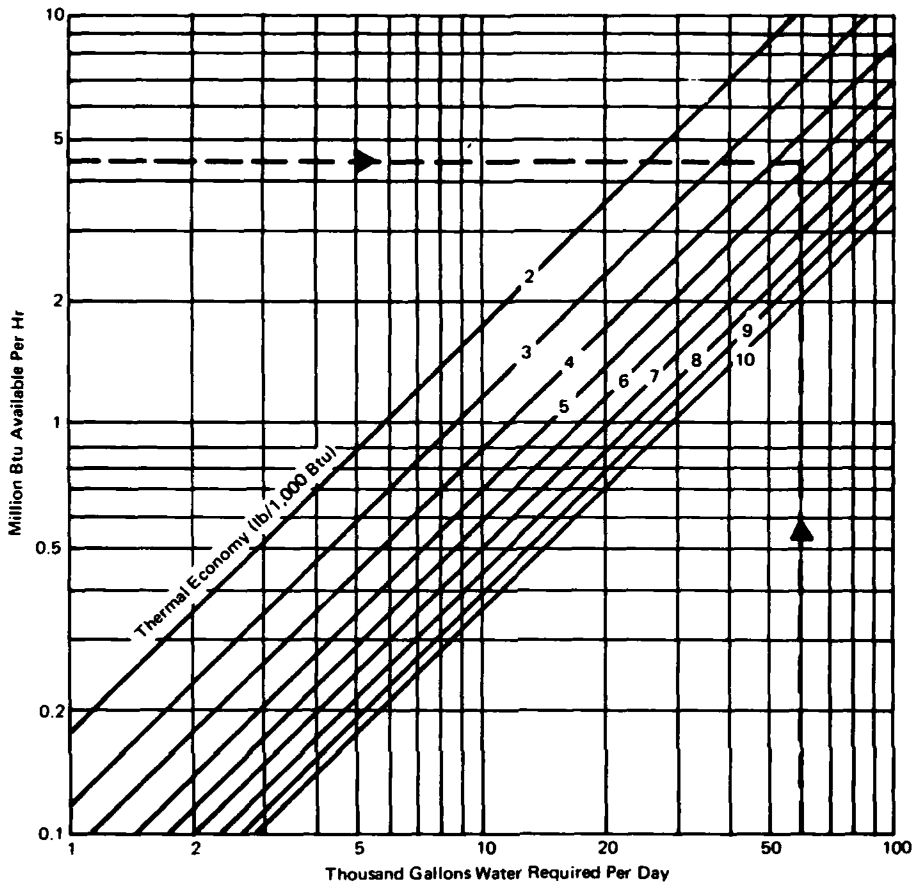


Figure A-2. Thermal economy chart.

Example 1c

It may be possible to use the exhaust heat from the diesel generators in addition to that available in Example 1a. For identical requirements, the waste heat available from the exhaust systems of each of the three units is read from Figure A-1 as 0.8 million Btu/hr, giving a total of 2.4 million Btu/hr. Adding this to the 4.5 million Btu/hr determined in Example 1a gives 6.9 million Btu/hr. From Figure A-2 the thermal economy is 3.0 lb/1,000 Btu, and from Figure A-3 it may be seen that a 16-stage unit would require a heat transfer area of 40 sq ft/1,000 gpd. For the total area of 2,400 sq ft (60,000 gpd required) the resultant cost is read on Figure A-4 as $72,000.

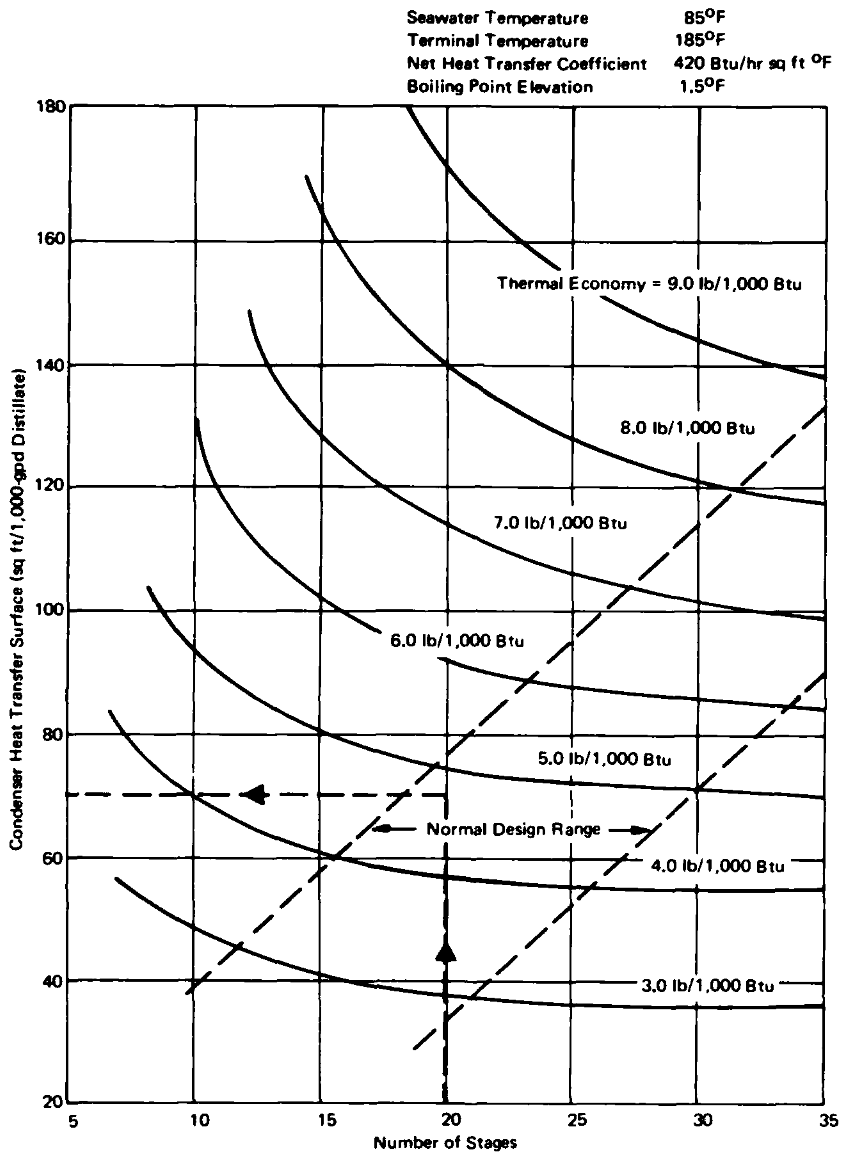


Figure A-3. Condenser heat transfer surface versus number of evaporator stages.

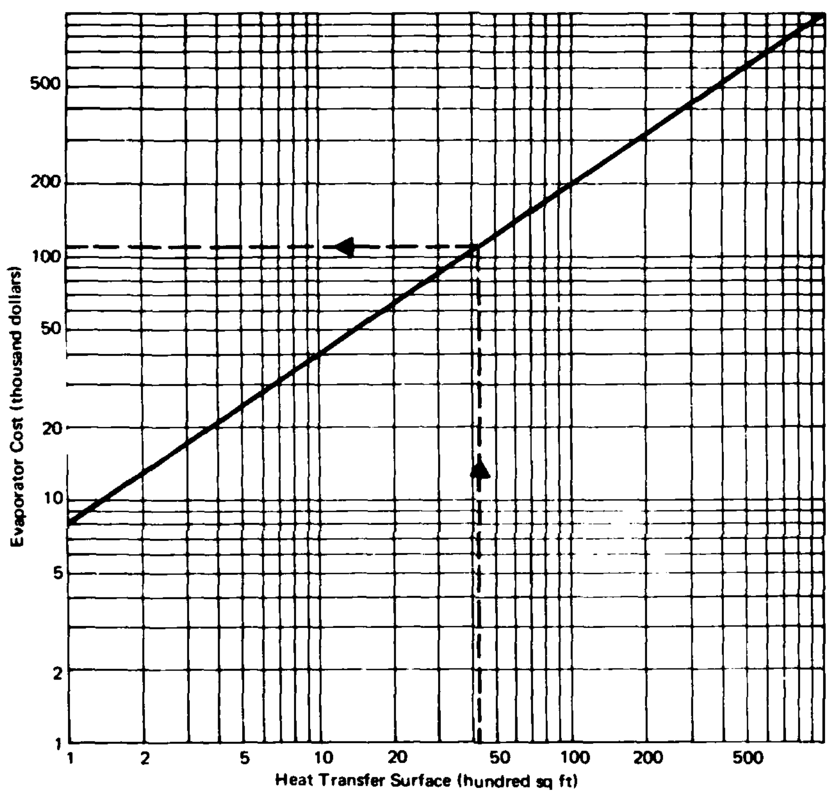


Figure A-4. Evaporator cost as a function of heat transfer surface.

Appendix B

COST OPTIMIZATION FOR MULTISTAGE FLASH DISTILLATION UNITS THAT UTILIZE DIRECT-FIRED BOILERS

If waste heat is not available for operating a multistage flash distillation plant, the energy is supplied from a direct-fired boiler. It is possible to determine the optimum cost for a distillation unit–boiler combination if the cost of the boiler, the water demand, fuel cost, and expected life of the plant are known.

The optimization procedure is based on the fact that as the thermal economy of the plant increases, the distillation unit becomes more expensive (greater number of stages required) but the boiler becomes smaller (less heat required). Thus there is an optimum where the total cost of the distillation unit and the boiler is at a minimum.

There are three variable cost items which are part of the annual cost of operating a multistage flash distillation plant:

1. The capital cost of the evaporator and supplemental equipment. This is directly proportional to the heat transfer area required and indirectly proportional to the length of the plant's useful life.

2. The cost of the steam plant. This is directly proportional to the rated steam capacity and indirectly proportional to the plant's expected life.

3. The cost of the fuel. This is equal to the amount used multiplied by the price of fuel at the plant.

It is possible to relate these three costs in graphical form to show the minimum total annual cost for a given plant output.

It is assumed that the water demand has been established. From Figure A-2 the heat to be supplied by the boiler (million Btu/hr) can be read for any selected thermal economy. The heat transfer area/1,000 gpd may be determined from Figure A-3 for the selected thermal economy within the normal design area. The midpoint of the curve, within the normal design area, is suggested to determine the cost and the number of stages. Figure A-4 provides the total evaporator cost. The boiler must supply the heat required for evaporation determined from Figure A-2 above. The cost of such a boiler should be determined from the appropriate sources. Fuel costs to operate the boiler should also be calculated.

The annual cost of the equipment, evaporator, and boiler is found by dividing the total cost by the expected life. The total annual cost is the sum of equipment and fuel annual costs.

The above calculations should be performed for several (at least three values of thermal economy, and a graph should be drawn of annual cost against thermal economy. This graph will show an optimum thermal economy for a minimum annual cost.

The following example will serve to illustrate the procedure.

Example 1

Water demand—60,000 gpd
Life expectancy of equipment—5 years

Step 1. From Figure A-2, for the stated water demand, 3.5-million Btu/hr should be supplied at a thermal economy of 6 lb/1,000 Btu.

Step 2. From Figure A-3, at a thermal economy of 6 lb/1,000 Btu in the normal design range, the evaporator will have 30 stages and require 86 sq ft of condenser heat transfer area per 1,000 gpd of distillate, or 5,160 sq ft for 60,000 gpd.

Step 3. The total evaporator cost is read from Figure A-4 as $125,000.

Step 4. The boiler must supply 3.5 million Btu/hr, which is equivalent to a little more than the output of a 100-hp boiler. The cost of such a boiler is taken as $7,500.

Step 5. Fuel costs for the boiler at 0.3 gallon of fuel/hp hr and $0.05 per gallon is equal to $13,800 per year.

Step 6. The annual cost of equipment is the total cost divided by life expectancy (5 years) or $1,500 and $25,000 for the boiler and evaporator, respectively.

Step 7. The above calculations are repeated for several values of thermal economy, and the annual costs are shown in Figure B-1.

Step 8. The annual costs are summed and plotted, as shown in Figure B-2. Curves have been drawn for several fuel costs, and optimum annual costs are indicated by the arrows. The curve drawn through the minimum points on the cost curves represents the optimum conditions for various fuel costs.

Step 9. The optimum plant for a given situation may now be selected. If fuel costs $0.05 per gallon, the thermal economy for optimum conditions is 5 lb/1,000 Btu. From Figure A-2 the boiler required to fulfill the conditions (60,000 gpd and a thermal economy of 5 lb/1,000 Btu) must supply 4.3 million Btu/hr. From Figure A-3 the distillation unit will require 25 stages and a heat transfer area of 73 sq ft/1,000 gpd or 4,380 sq ft.

N.B. The above figures are used for example only; boiler and fuel costs should be ascertained for each individual situation.

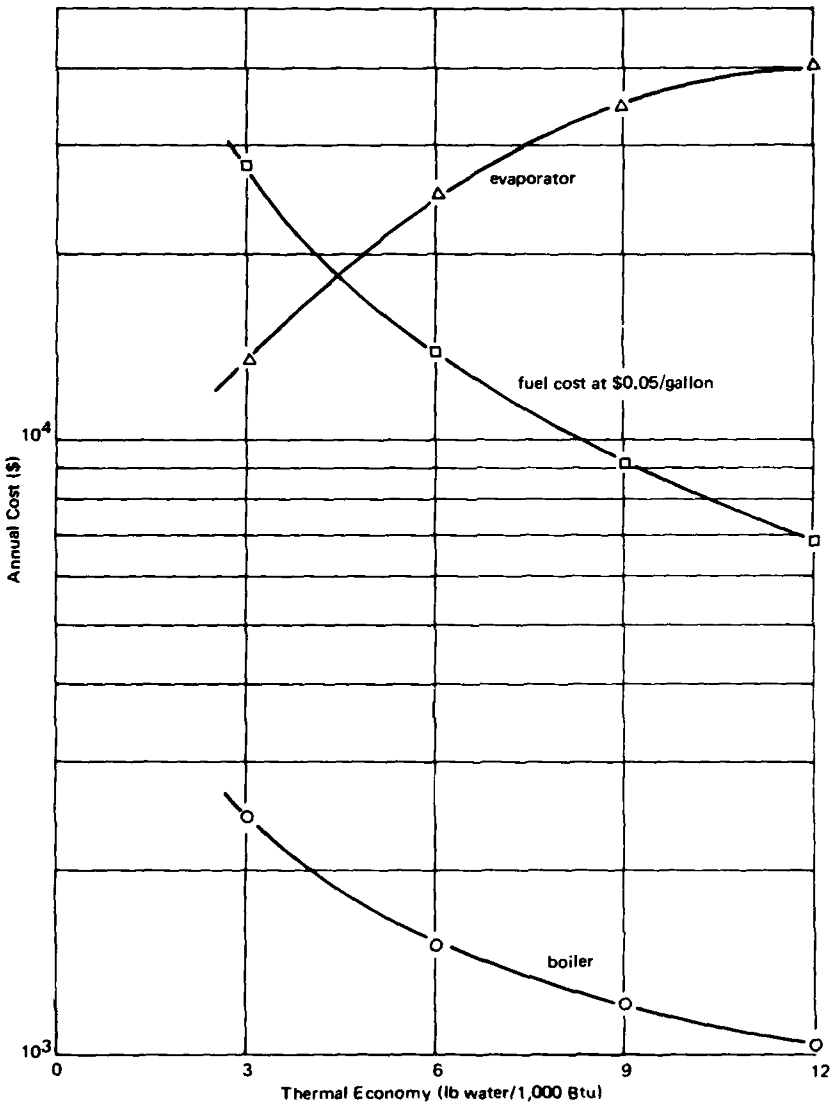


Figure B-1. Annual costs for multistage flash distillation plant.

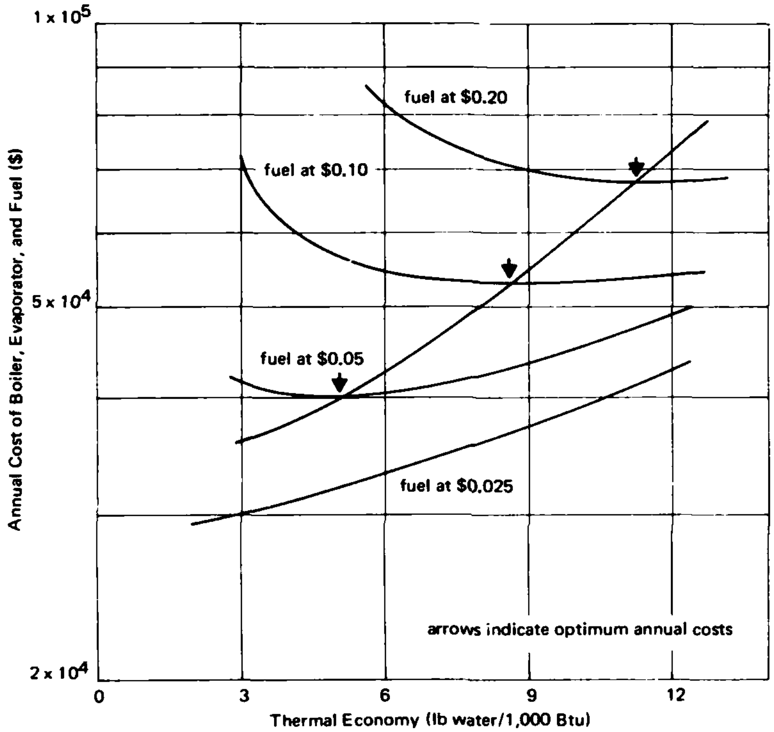


Figure B-2. Optimization of 60,000-gpd multistage flash distillation plant that utilizes direct-fired boiler.

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13. ABSTRACT

This report summarizes the desalination processes currently available which lend themselves to military application. Membrane processes (electrodialysis and reverse osmosis) and thermal processes (multistage flash distillation and vapor compression distillation) are explained, and examples of the use of each type of equipment are cited. Design criteria are given for multistage flash distillation units utilizing waste heat from diesel generators. An optimization procedure is also given for similar units using direct-fired boilers.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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